The Improved Electric Micrometer.

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I. *Introduction.*—The electric micrometer was first used for the measurement of the amplitude of a telephone diaphragm.* It was exhibited at the Royal Society Soirée in May, 1900. A succession of papers have followed in which the same principle has been applied to other measurements.† The apparatus used in these last papers is in every way an advance on the first one. It is described below for the first time.

The work done since 1900 has established the reliability of this method of measurement, and seems to show that the limit to its practical sensitiveness (a unit of 4×10^{-8} cm.) has been attained. It may be well, therefore, now to state in detail the form, peculiarities, and limitations of the apparatus.

II. *The Instrument.*—In the drawings fig. 1 is a side elevation of the micrometer and electric circuit; fig. 2 is an elevation, enlarged, showing details of the levers; fig. 3 is a cross-section on the line A′A′, fig. 2; fig. 4 on the line B′B′, fig. 2; fig. 5 is a section showing the contacts P, Q; fig. 6 is a diagrammatic view of the instrument and suspension.

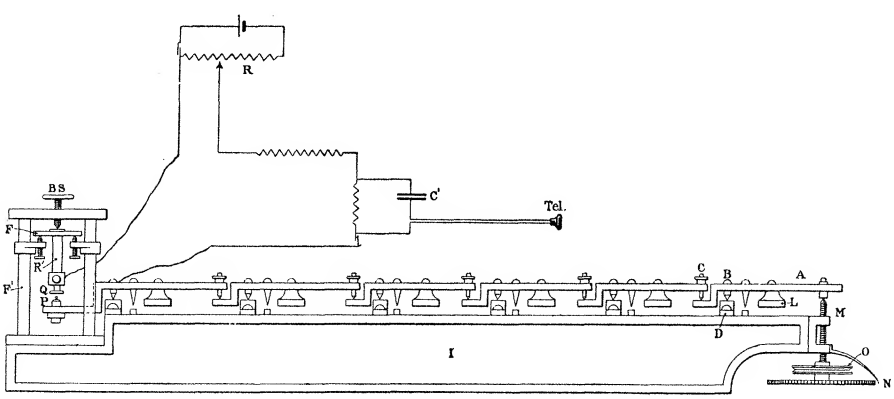


Fig. 1.

In fig. 1 are shown six levers of steel A fitted to turn on fulcra B, the long arm of one lever being actuated by the short arm of the next through

* Shaw, 'Phys. Soc. Proc.,' vol. 17, and 'Phil. Mag.,' December, 1900.

† Shaw, 'Phil. Mag.,' 1901; Shaw and Laws, 'Electrician,' 1901 and 1902; Shaw, 'Roy. Soc. Proc.,' 1903; Shaw, 'Roy. Soc. Proc.,' 1904.

pointed pins C. The fulcra blocks D, which are of hardened steel and have a true surface, are attached to the massive girder I of cast iron, and are surrounded by a metal casing E (fig. 2) which forms the sides of a bath for oil. The fulcra are 1 inch wide, and rest only on two small knife-edges which are at the sides of the fulcra as shown in fig. 4. The knife edges are of hardened steel.

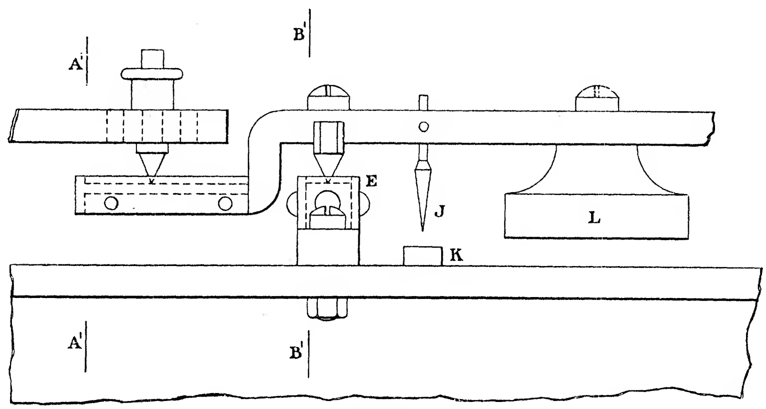


Fig. 2.

The short end of the levers are fitted with a hardened steel plate G (fig. 3), and with a metal casing H which forms the sides of a bath for oil. The pin C in the long end of the levers (except the first) is fixed by a nut, and the ends of the levers are provided with three holes for these pins so that leverage can be varied (see fig. 2).

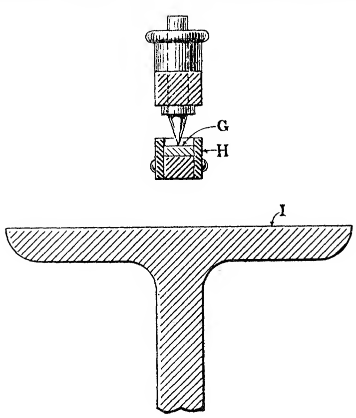


Fig. 3.

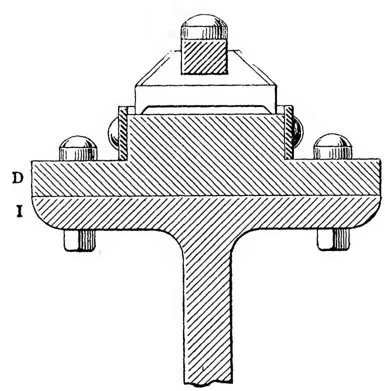


Fig. 4.

The levers are also fitted with pointers J, and the girder has index plates K by which the position of each lever can be fixed, or a template can be used between J and D for the same purpose.

Each lever is also provided with a weight L which gives firm pressure of the levers on the blocks and on one another.

The end of the long arm of the first lever is in contact by a polished agate plate with the point of the micrometer screw M, which has 20 threads to 1 cm., and whose nut is attached to the girder. The usual free nut and spring is used to reduce back-lash.

The lower end of the screw has a divided wheel N and a pulley O. The angular movement of the screw can be ascertained by watching in the telescope (fig. 6) the reflection in the mirror *m*, the under graduated face of N. The end of the last lever is fitted with a spherically-ended pin P (fig. 5) of iridio-platinum.

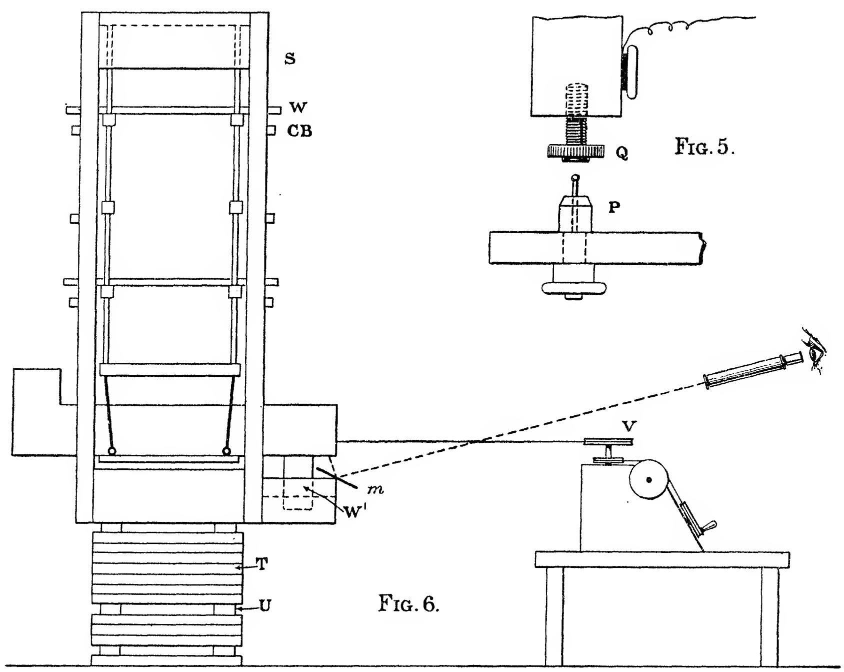


FIG. 5.

FIG. 6.

The fixed measuring surface Q is carried by a spindle R′ from a plate F above, the position of which can be adjusted in the frame F′ by the adjusting tripod screws shown at the side, and by the binding screw BS at the top. The whole frame and its attached parts are firmly fixed to the girder.

The instrument is enclosed in a felt-covered box, and is suspended by rubber springs from the top of a massive frame S, which itself rests on a pile of heavy concrete slabs T (2 feet square) with rubber cushions U at intervals. The tension of the springs may be adjusted by weights W, and

there are rails CB to prevent these weights falling on the micrometer in case of breakage.

The screw is actuated by an elastic cord driven by a pulley V which is on an independent table. To reduce the movement set up by the working of the pulley cord, the underside of the box has a plunger W′ working in a dash-pot of castor oil.

The vertical movement of the screw actuates the system of levers, the extent of the movement being reduced by each lever in succession, and when the point P touches the fixed surface Q, an electric circuit is completed, and the telephone *tel.* sounds, as it also does when P and Q separate again.

The circuit shown includes a cell, potential divider R, high resistances telephone, and a condenser C′.

As regards dimensions, the height of fig. 6 is 10 feet and the parts are in proportion. The lever system is 3 feet long. Each lever is 6 inches long and is made of $\frac{1}{4}$-inch square bar. The girder is 4 inches deep, and its material is $\frac{1}{2}$-inch thick. The frame F′ is small and massive for the sake of rigidity.

III. *Setting and Using.*—Suppose, as an example, we wish to find the magnetic expansion of the rod R′ (fig. 1), *i.e.*, the amount it changes in length when a known current is sent through a solenoid of which R′ is core.

Remove the plate Q, by unscrewing, and also the last lever which carries P. Polish P and Q with dry rouge on wash leather and finally with clean wash leather. Replace Q and the lever.

We have now to make P and Q come *just* into contact; this is a very delicate adjustment.

Put the telephone *tel.* to the ear. Adjust the three tripod screws and the binding screw BS on the top of the frame F′; the former work up and produce level while the latter works down. The whole system can be obtained rigid with P and Q just in contact, this contact being shown by the sounding of the telephone.

So far we have obtained only rough contact. To bring P and Q into *bare* contact, proceed to the pulley V (fig. 6) and wind the pulley cord, turning the screw M until the telephone sounds again.

This gives the *exact* position of contact. There will be a steady "creep" of the contact position for a considerable time after the covers have been put in place. Accurate work can be done when temperature equilibrium is established in, say, 15 minutes. The wheel N is watched and readings on it corresponding to the contact "make" and "break" are noted.

Change the magnetic field on R′ by known amounts and note the corresponding changes in the contact positions of P, Q.

If the joint leverage come to 1000/1 and the screw pitch be 1/20 cm., with 500 graduations on N the unit of the instrument will be 10^{-7} cm.

IV. *Calibration.*—This can be done by measuring all the lever arms and multiplying the joint leverage into the unit of the micrometer screw. A better method is to use optical interference. Remove the plate Q and spindle R′ and mount a glass plate, with a worked surface face downwards, in place of them. On the top of pin P put a convex lens of small curvature. Newton's rings can be produced in the usual way between plate and upper lens surfaces. Use sodium light and watch the rings with a microscope.

On working the screw M up or down the pin P rises and the rings grow from or contract into the centre, respectively.

Take readings of the screw head for every ten rings passing one point and calculate at once the unit. The following is a sample table:—

Units on wheel N corresponding to 10 rings.			
Up.	Up.	Down.	Down.
5900	5930	5950	5850
5920	6000	5900	5900
5920	5950	5870	5880
5940	5900	5940	5900
5900	5850	5900	6000
5880	—	5850	—
Mean ...	5920	Mean ...	5890

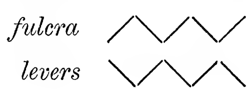
Thus 590 units correspond to 1 ring $= \lambda/2$.
" 1 unit " $= 4{\cdot}9 \times 10^{-8}$ cm.

The wave-length is a standard unit of the order μ and is 1200 times the unit of the instrument. It would be an advantage to have a standard unit of the order of the instrument, *i.e.*, $\mu\mu$. The greatest and least readings in the above table differ by about 2 per cent. This large error is partly due to inaccuracy in reading the edge of the rings (this might produce 1 per cent. error on 10 rings), but is also due to the fact that the cover is not on the contacts during this calibration, so that thermal expansions occur in them. The cover could be on during calibration, but in the present case it was not considered necessary.

V. *Sources of Error: Precautions.*

Movements are Normal to Contact Surfaces.—The levers are bent in order that (*a*) the turning edges of the fulcra, (*b*) the contact point of each lever on the next, (*c*) the contact of screw on the first lever, and (*d*) the contact P and Q where measurements are made, should all lie in one horizontal plane. Thus when the actuating screw works up or down by a small amount there is normal displacement at every contact surface and no scraping of one surface on another. If only these small movements are made we can thus avoid end strain among the levers or actual sliding, which would cause sudden alteration in leverage and jerky working.

Strains in Levers.—The levers conspire to produce minification, each long arm rests on the next short arm and is moved by it. There is no large stress anywhere in the system. The actual pressures (*a*) between fulcra and blocks, and (*b*) between lever and lever have alternate maxima and minima from end to end of the system, the greatest differences being at the left end of the system. But the strains are all due to constant gravitation stresses. There seems no reason to expect that in such a set of well-oiled contacts, irregular strains should arise from the mere working of the system, when measurements are made. In actual trial the micrometer is found to work so uniformly that one feels confident that the strains are exceedingly regular, and that each link in the system used does add accuracy as well as sensitiveness.



Longitudinal Displacements.—The levers are allowed three degrees of freedom, a rotation on vertical axis, a translation across the girder and a translation along the girder. In each case the play is very small. It is very desirable that the levers should have freedom without using it.

It is important to have the levers equispaced, for if the small arms have the same length in each lever, a small longitudinal displacement of any lever (except the first and last) will not seriously change the total leverage. Thus suppose the second lever, fig. 1, be moved a small distance to the right, the first lever will gain and the second will lose leverage in the same ratio. But if the movement be continued, the short arms of the two levers being now unequal, the first lever gains leverage in greater ratio than the second loses it. The first and last levers are exceptions. If the first lever move by a small amount to the right it *alone* loses leverage. If the last lever move to the right, the fifth lever *alone* gains leverage. Hence the first and last levers should not be allowed to move longitudinally during an experiment.

If work of high accuracy is being done, it is therefore necessary to frequently set the levers in those exact places for which the instrument has been calibrated. The two other degrees of freedom would produce errors of a smaller order.

The Oil Baths.—These (1) lessen jerk in case the levers slide, and (2) keep the contacts free from dust and from corrosion by contact with the air. It will be seen that of the 13 contact places in the lever system only two are exposed to the air, the first and the last. If particles of dust were allowed to fall on the contact surfaces, they might work into the contact, producing serious error, especially at the left end of the instrument. Dust falls on the oil surface and floats there, the contacts below being thus kept clean.

Vibrations.—Tremors from the ground cannot easily reach the micrometer. There are two possible ways by which they can do so, (1) ascend through the massive cement slabs interleaved with rubber, pass to the top of frame S, then descend the rubber cords S′ which are loaded with 28-lb. bars at intervals, or (2) pass along the rubber pulley cord; but this is too light and lax to transmit such tremors as will affect the suspended body, weighing about 80 lbs.

Measurable tremors only reach the micrometer rarely. The above insulating arrangements act so well that ordinary measurements more than 5 $\mu\mu$ can be done throughout the day. Finer work is done at night after 12 o'clock. It may be mentioned that the instrument is set up in a vault, whose floor is 12 feet below ground level, and that a mechanical workshop is immediately overhead.

Thermal Expansions.—Expansion in the direction of the length of the apparatus can be ignored, whereas expansion perpendicular to the levers would introduce large error. The following parts, therefore, should, if possible, be made of invar—cage F′, spindle R′, pin P, lever pins C, fulcra B. But these vertical expansions become of decreasing importance as we pass from the cage F′ to the right of the apparatus, so that thermal expansion in the screw and last lever pin can be ignored. Suppose the spindle R′ is of brass (which must be used in magnetic work) and is 20 cm. long; if its temperature change 1°, the movement is 4×10^{-4} cm., *i.e.*, 10,000 units on the instrument, whereas if the first lever pin is of brass, and 1 cm. long, a change in temperature of 1° would be 5×10^{-9} cm., *i.e.*, 1/10 unit.

When a new set of measurements is about to be taken, it is always necessary to uncover the micrometer and clean the contacts P, Q. On putting the cover on again, thermal expansion will be seen in "creeping" of the contact. For the most delicate work, 1 hour and sometimes more is required for temperature equilibrium to be established.

Magnetic Strains.—When magnetic work is in hand, *e.g.*, magnetic expansion,* the girder and cage F′ and levers, and all bolts and nuts must be of non-magnetic substance.

The Contact Surfaces.—Steel, iron, platinum, copper, carbon, and other surfaces have been tried for P and Q, but iridio-platinum seems best of all, and dry rouge on washleather is used for polishing. High polish is essential for sharp readings. Again, the ordinary use of the surfaces, involving frequent make and break, damages them, say, in one hour of continuous use, and the readings become uncertain.

It has frequently been urged by critics that as the surfaces P, Q approach one another, having a potential difference of, say, 1 volt, there will be a spark between them before the surfaces touch, and that this sparking will be irregular and a source of uncertainty in the finest measurements. This sparking probably always occurs, but it is not irregular within experimental limits, as is shown by the fact that the readings of the instrument are consistent.

As regards the length of this spark-gap, the present writer has made investigations for low voltages, from 100 volts to 0·2 volt,† and has found that for P.D. 1 volt the gap is 10 $\mu\mu$, and that the relation between gap and P.D. is linear. Assuming a combination of the linear relation, and taking the P.D. used in the micrometer work, 1/100 volt, the gap would be about 1/10 $\mu\mu$. So that, whether regular to 20 per cent. or not, the sparking would introduce no measureable error.

VI. *Applicability.*—The method has been shown to be applicable to various measurements :—

(1) Telephone diaphragm movements and hence the amplitude of the least audible sound.‡

(2) The expansion of iron, steel, nickel, and of non-magnetic bodies when subject to changes of magnetic field.§

(3) As a coherer. The two contact points can be brought to molecular distance apart without touching; they then constitute a very sensitive and adjustable coherer.||

(4) The distance of discharge of two surfaces maintained at a different electric potential.¶

There are other obvious applications, *e.g.*, (*a*) thermal expansibility;

* See 'Roy. Soc. Proc.,' 1903.
† See 'Roy. Soc. Proc.,' 1904.
‡ See 'Phil. Mag.,' 1900, and ensuing paper.
§ See 'Electrician,' 1901 and 1902, and 'Roy. Soc. Proc.,' 1903.
|| See 'Phil. Mag.,' March, 1901.
¶ See 'Roy. Soc. Proc.,' 1904.

(*b*) the Newtonian constant, by the measurement of the movements of a pendulum from the vertical under the attraction of a large mass.

VII. *Comparison with other Micrometers.*—Other instruments capable of fine measurements are :—

(*a*) *The Optical Lever,* on the Gauss-Poggendorff principle. The movement to be measured causes rotation of a mirror, so that a spot of light from it traverses a scale. In some cases levers are used to magnify the effect.* The form used by Nagaoka† is very sensitive: there is no lever, but the movement of the spot is examined by a microscope. The smallest recorded reading in this way is $2{\cdot}3 \times 10^{-7}$ cm.

(*b*) *Interference Methods.*—The Fizean method has been developed by Abbé, Pulfrich, and Tutton. The distance between the interfering surfaces is small.

The interferimeter, where the interfering surfaces are far apart, has been developed by Michelson into an accurate and adaptable instrument. The unit in these methods is about 10×10^{-6} cm. The objection to these methods is that the interference bands are so far from sharp that it is difficult to locate accurately the centres of two consecutive bands, and to divide the intervening space into any number of equal parts.‡

(*c*) *The Microscope.*—This is still less sensitive than interference methods, the smallest possible reading being 2×10^{-5} cm.

To enumerate the qualities desirable in a micrometer :—

(i) *Practical Sensitiveness* (*i.e.*, the smallest distance which can be accurately read)—

The electric micrometer ...	4×10^{-8} cm.
optical lever	$2{\cdot}3 \times 10^{-7}$,,
interference methods ...	1×10^{-6} ,,
microscope	2×10^{-5} ,,

(ii) *Range.*—The electric micrometer can read quite 10,000 units $= 4 \times 10^{-4}$ cm.

In the other micrometers there is a field of view which determines the range. Or, if a micrometer screw be used to restore zero reading, the practical sensitiveness is that of a *working* screw, which is not great.

(iii) *Quickness of Action.*—The optical lever, interference methods, and

* See Shelford Bidwell, 'Phil. Trans.,' A, 1888.

† See 'Phil. Mag.,' 1894.

‡ Recently, a modification of Michelson's method has been made by C. W. Chamberlain (see Kinsley, 'Phil. Mag.,' May, 1905), by which the sensitiveness is greatly increased, and movements of 3×10^{-7} cm. have been measured.

microscope, are quick within the range of the field of view, outside that range they are at least as slow as—

The electric micrometer, in which time must be taken for the movable contact to bridge over the gap to the fixed contact.

(iv) *Calibration.*—The interference methods here have an advantage over other micrometers in that no calibration is necessary, the wave-length being a standard known length.

The electric micrometer and the microscope can be readily calibrated, the former by interference bands, and the latter by a line standard bar.

The optical lever cannot be calibrated with accuracy; any method takes account directly or indirectly of the effective length of the lever. This length is small and diffcult to measure with precision.

(v) *Freedom.*—In the interference methods and microscope the measuring apparatus does not press on the moving body, so this need not be rigid. This is an advantage.

In the optical lever and electric micrometer, actual mechanical pressure, though not necessarily large, is essential. If perfect freedom of the moving body is required, these methods are inadmissible.

(vi) *Compactness.*—The optical lever is the most simple and compact micrometer, and the electric micrometer is the least so, in the form described above. But the latter instrument could, if desirable, be reduced to quite a small size, without detriment to its usefulness.

I am glad to acknowledge my indebtedness to the Royal Society for two grants in aid of these researches, and to Professor W. H. Heaton for his unfailing encouragement and general furtherance of the work.